



Permeability of the weathered bedrock aquifers in Uganda: evidence from a large pumping-test dataset and its implications for rural water supply

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Abstract

Weathered crystalline-rock aquifers underlie around 40% of sub-Saharan Africa providing water supplies for half of its rural population; they are also prevalent across the tropics. The hydrogeology of these aquifers is complex and better understanding of the controls to aquifer transmissivity, alongside accurate borehole siting and appropriate design, is pivotal to the long-term performance and sustainability of water services in many countries. This study examines a substantial new dataset ($n = 655$) of aquifer transmissivity values across Uganda derived from previously unanalyzed pumping-test data. These data provide important new insights: weathered crystalline-rock aquifers are distinguished by pervasively low transmissivities (median $< 2 \text{ m}^2/\text{d}$) in comparison to other areas in the tropics; highest transmissivities are observed in boreholes $< 50 \text{ m}$ deep, implying that drilling deeper boreholes does not typically improve supply success or sustainability in Uganda; and increased groundwater abstraction through the use of higher-yielding pump technologies will prove challenging in most areas of Uganda and limit their use for piped water supplies. This study highlights the scientific value of data held in drillers' records, which remain unanalyzed in many countries but may provide useful insight and understanding of aquifer characteristics.

Keywords Groundwater development · Weathered bedrock aquifers · Crystalline rocks · Permeability · Uganda

Introduction

Water supplies based on groundwater are considered more climate resilient than surface-water alternatives (Taylor et al. 42; Gaye and Tindimugaya 16; MacAllister et al. 24), and have been shown to sustain livelihoods during periods of drought throughout different parts of sub-Saharan Africa (Tucker et al. 46; MacDonald et al. 28). The development of groundwater as a resource, therefore, is a key component of efforts to extend water supply coverage to the poorly served and to accelerate progress towards the UN Sustainable Development Goals (Upton and MacDonald 47). Groundwater is not, however, universally available; local hydrogeological conditions determine the volume of groundwater that can

be sustainably developed or whether groundwater is present at all. Some of the most complex aquifers are those found in weathered crystalline rock. The hydrogeology of these aquifers is complex and well yields are almost entirely dependent on the nature of the weathering profile and the number of intersecting water-bearing fractures at depth, as well as the presence and thickness of overlying unconsolidated deposits (Acworth 1; Chilton and Foster 10; Taylor and Howard 40; Bonsor et al. 9; Bianchi et al. 7).

Weathered crystalline-rock aquifers underlie around 40% of sub-Saharan Africa, providing water supplies for half of its rural population (MacDonald et al. 27, 25); they are also prevalent across much of the tropics (Lachassagne et al. 23). The majority of these water supplies in tropical Africa are low yielding ($< 0.5 \text{ L/s}$) and primarily operated by handpumps. Previous studies have reported a high incidence of well failure and low yields over the past four decades (Chilton and Smith-Carrington 11; Howard and Karundu 21; Owor et al. 31; Bonsor et al. 8). Aquifer transmissivity can be a key limitation on well yields and long-term sustainability of groundwater withdrawals; transmissivities of less than $1.4 \text{ m}^2/\text{d}$ are shown to be a cutoff for the

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sustained operation of HPBs (Bianchi et al. 7). Even with the low yields demanded by a handpump, many water supplies are unreliable or fail altogether (Owor et al. 31). A yield of >10 L/min (>0.17 L/s) is generally considered the minimum yield required for a HPB to deliver required water for a community supply.

There is considerable pressure to source higher yielding water supplies from crystalline-rock aquifers which, although possible, are rare (Taylor et al. 43; Maurice et al. 29; Bianchi et al. 7). The need for higher yielding supplies is driven by pressure for increased development of groundwater for irrigation and piped drinking-water supplies (Gaye and Tindimugaya 16; Cobbing 12), and the increased availability of solar-powered pumps (Wu et al. 50). There is consequently an urgent need to understand more about the variability in the aquifer properties of weathered crystalline-rock aquifers, and to map aquifer properties across larger areas. This study maps the aquifer properties of crystalline-rock aquifers across Uganda, a country highly reliant on this aquifer system for its drinking-water supplies.

Crystalline rocks of Precambrian age underlie nearly three quarters of Uganda (Schlüter, 36; Westerhof et al. 48). Despite the relatively low storage of these weathered and fractured bedrock aquifers, they are actively recharged (Taylor and Howard 38; Owor et al. 30; Cuthbert et al. 14; Banks et al. 2; Lapworth et al. 22). These aquifers underpin the majority of community groundwater supplies in both rural areas and urban growth centres in Uganda (Taylor et al. 41; Tindimugaya 45).

Across Uganda the main technology options used for water supply in rural areas are community boreholes with handpumps (45%), shallow wells (23%), and protected springs (21%); these enable access nationally to an improved water source of 68% (GOU-WESPR 20). Other technology options include rainwater-harvesting schemes and shared tap stands to reticulated/piped supplies. Development of groundwater for piped water supply is the focus of efforts to improve access to safely managed water across rural areas in Uganda (GOU-WESPR 20). Increasing access to basic drinking-water services through community hand-pumped boreholes (HPBs) is, however, likely to remain the primary pathway towards increasing water services in the country over the next decade, despite the emphasis of the UN Sustainable Development Goals (SDGs) for universal access to household supply (WHO/UNICEF-JMP 49). Under the second national development plan (2015–2020), access to improved community supplies in rural areas increased from around 65–75%, and the target now set under the third national development plan is for this access to increase to 85% by 2025 (GOU NDP II 18; GOU NDP III 19). The development and performance of water services supplied by groundwater in Uganda are greatly influenced by geology and the predominance of weathered crystalline rocks. The

low permeability of weathered crystalline-rock aquifers is thought to limit groundwater potential so that careful siting of boreholes is essential to achieve functional and sustainable hand pumped boreholes (Taylor and Howard 40; Graham 17; Owor et al. 31).

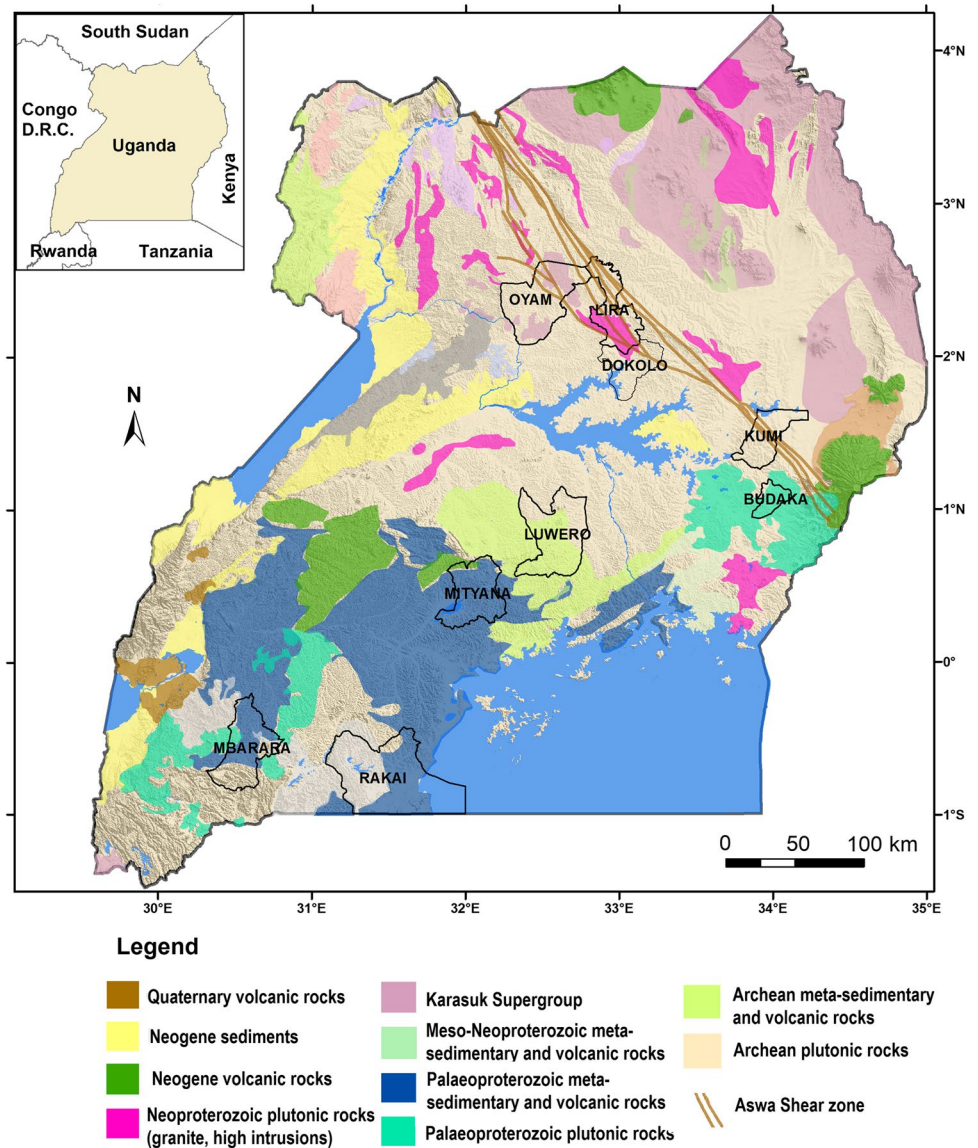
To better understand the opportunities and restrictions posed by weathered crystalline-rock systems on groundwater development in Uganda, and what impact these have on groundwater development in the country, a newly collated dataset of aquifer transmissivity values across Uganda, derived from 655 previously unanalyzed pumping tests, was interrogated. These data provide new insight into the physical capacity of weathered crystalline-bedrock aquifers across Uganda to meet increasing freshwater demand and the possibility of higher groundwater withdrawals via technologies such as solar-energy pumps.

The geology and geography of Uganda

Much of Uganda is located on the East African plateau, and has an elevation of 800–2000 m above sea level in most areas, apart from the higher mountainous regions along the western and eastern borders (Owor et al. 33). The majority of the country sits within the drainage basin of the River Nile; Lake Victoria forms the source of the White Nile. Uganda has a tropical climate, with average annual rainfall 600–1,600 mm and temperatures of 18–28 °C (Owor et al. 33). Whilst rainfall occurs throughout the year, there are two wetter seasons which occur between March and May, and September and November. There is also notable spatial variation in climate and land cover from rainforest in the south to hotter savannah conditions in the north (ESA GlobCover 2.3 15; Owor et al. 33).

The geology of Uganda comprises Archaean lithospheric fragments, welded together, intersected or surrounded by Proterozoic fold belts (Schlüter 36; Westerhof et al. 48). Uganda forms a part of the northeastern corner of the proto-Congo Craton, composed of several Archaean nuclei and Palaeoproterozoic mobile belts (Fig. 1). The fold belts are related to the Eburnian (2.20–1.85 Ga), Grenvillean (1.10–0.95 Ga) and Pan-African (0.75–0.50 Ga) Orogenic Cycles. There are also molasse-type platform deposits, post-orogenic to each of the preceding cycles that include post-Pan-African deposits in Karoo basins and the two branches of the Neogene East Africa Rift System. The Archaean and Neoproterozoic plutonic rocks which underline northern and eastern parts of Uganda are predominantly gneissic and amphibolite rocks with variable gneissic granitoids, granulites, marbles, and quartzites (Schlüter 36; Westerhof et al. 48). Within central and southwestern Uganda, Palaeoproterozoic and Meso-Neoproterozoic meta-sedimentary and

Fig. 1 Regional geology of Uganda (after Westerhof et al. 48) indicating the nine survey districts. The geological map shown is based on mapping work by Geological Survey of Finland (GTK), published as Westerhof et al. 48



volcanic rocks are also present, along with Neogene volcanic rocks.

The hydrogeological properties of the Precambrian crystalline rocks in Uganda derive from biogeochemical and physical weathering. Regional-scale fracture networks (e.g. Aswa shear zone, Fig. 1) are associated with tectonic activity in this area, and are nestled between the eastern and western arms of the East African Rift System. As argued by Taylor and Howard (37, 40), the landscape and its underlying hydrogeology can be understood, in part, in terms of the long-term, tectonically controlled cycles of deep weathering and erosion. Following late Palaeozoic glaciation, more humid and warmer climates through the Mesozoic Era led to the development of thick weathered profiles (i.e. saprolite/regolith) during a long period of tectonic quiescence.

Miocene rifting and late Pliocene downfaulting of the western arm formed lakes Albert and Edward (Fig. 2a) and established new base levels of drainage that served to initiate erosion (truncation) of weathered profiles draining to the rift from western Uganda (Fig. 2a). In central and eastern Uganda, late Pleistocene downwarping along a north–south transect reversed western drainage to the Congo basin and led to the formation of lakes Kyoga and Victoria (Fig. 2a), enabling continued deep biogeochemical weathering of crystalline rock formations. This geomorphological context explains large-scale variations in the thickness of regolith profiles that can provide vital groundwater storage to sustain well yields from the regolith directly or via the underlying fractured bedrock in weathered crystalline-rock aquifer systems (e.g. Acworth 1; Taylor and Howard 40; Bianchi

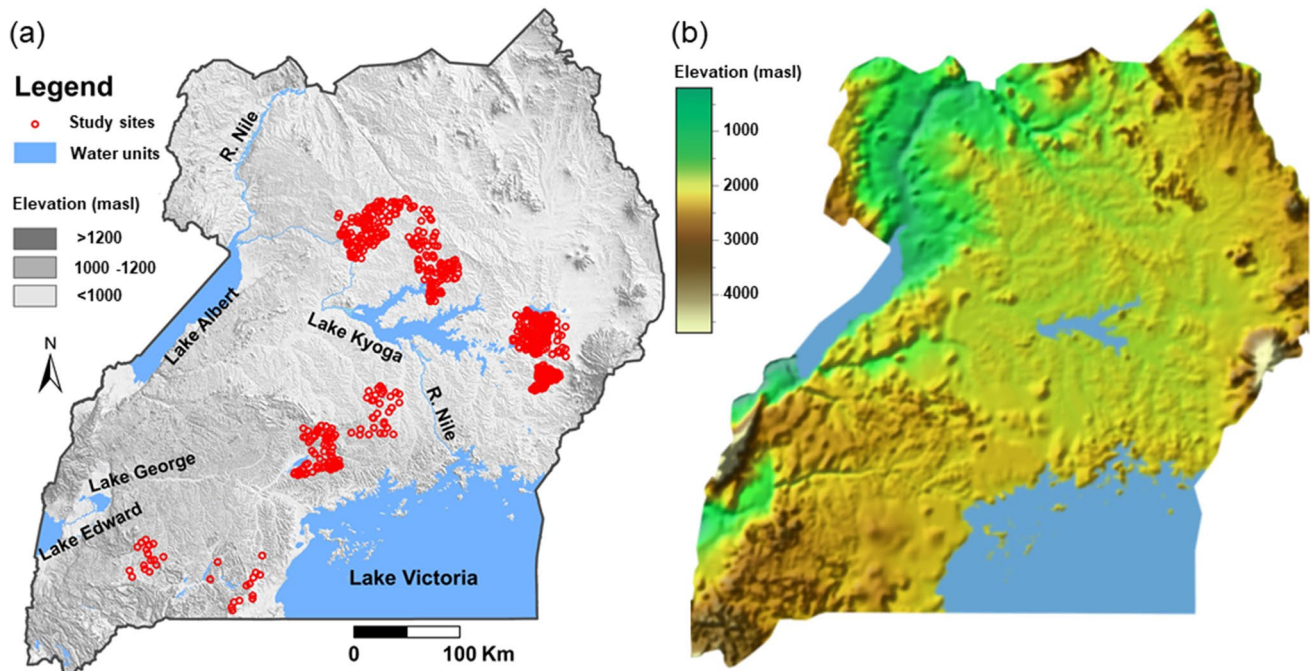


Fig. 2 **a** Map of Uganda illustrating the distribution of the study sites; and **b** the regional topography and relief across Uganda. Elevation data (in meters above sea level, masl) are based on a digital elevation

model (DEM) of Africa derived from the open access US Geological Survey (USGS) Global 30 Arc-Second Elevation dataset (GTOPO30)

et al. 7). The borehole locations used in this study occupy, however, the headwater regions of rift-induced drainage and the crystalline-rock aquifer systems have yet to be strongly influenced by the current cycle of erosion (Fig. 2). Observed regolith thickness in this study is thus expected to be primarily a function of the weatherability of the parent bedrock. The extent of fracturing in the underlying bedrock derives from not only tectonic activity but also by erosional unloading (i.e. isostatic uplift/sheeting) associated with regolith development.

Methods

Collating the pumping test data

The study developed a dataset of 655 previously unanalysed pumping tests across Uganda that were compiled from historical borehole records held within nine district water offices, Fig. 1. These data originated from numerous drilling campaigns undertaken by private contractors in each district to site and construct HPB water supplies between 2000 and 2018. Developing the dataset comprised a substantial manual data-compilation exercise. Each of the 9 district offices was visited, where over 1000 hardcopy borehole records were collated and reviewed over several

months. From these, 752 borehole records with pumping-test data were identified. These records were scanned and transcribed to create a digital dataset. Each borehole record in the dataset contains a series of metadata alongside the pumping test data (e.g. pump depth, static water level, pumping rate and duration), including locational information (e.g. coordinates, water strike, yield, drilling method), borehole lithologies (drilling depth, lithology), and well design details (e.g. well diameter, material). For some borehole records additional water chemistry data (e.g. pH, electrical conductivity, EC, alkalinity, Ca, Mg, total Fe, HCO_3 , SO_4 , NO_3 , PO_4) and geophysical data (e.g. resistivity profiling, vertical electrical sounding) were also present. None of these data had previously been analyzed.

The generated dataset extends across the northern, eastern, central and western regions of Uganda (Fig. 1) and includes sites within the Basement Complex (Archean meta-sedimentary, plutonic and volcanic rocks) and weathered Precambrian meta-sedimentary formations in Uganda. Based on recent work by Westerhof et al. (48), the main regional geological formations represented by the dataset can be grouped into three categories: (1) gneissic basement (Archean basement and some post-Archean formations); (2) Precambrian metasedimentary bedrock (a mixture of meta-sedimentary and volcanic rocks); and (3) plutonic basement (Archean plutonic rocks). Table 1 shows the distribution

Table 1 The distribution of the hand-pumped boreholes (HPBs) data analysed from nine districts in Uganda

District	Main geology	No. available HPBs datasets	No. analysed HPBs datasets
Luwero	Gneissic basement	38	32
Mbarara	Precambrian meta-sediment	22	18
Mityana	Precambrian meta-sediment	85	73
Rakai	Precambrian meta-sediment	14	14
Budaka	Plutonic basement	136	119
Dokolo	Plutonic basement	75	67
Kumi	Plutonic basement	207	173
Lira	Plutonic basement	46	39
Oyam	Plutonic basement	129	120
Total datasets		752	655

The main geology category reflects the dominant geology represented by the dataset in each district as indicated by Westerhof et al. (48). A smaller number of other geological categories are present in the dataset within each district, as well as the main category

of these categories across the dataset sample and districts. The main rock types observed within these categories by Westerhof et al. (48) are summarised in Table 2.

Table 2 The main rock types observed within the categories of bedrock geology in Uganda, as summarised by Westerhof et al. 48

Main geology	Main Rock type
Gneissic basement	Granites, granite gneisses, biotite and hornblende gneisses, quartz–feldspar–biotite–muscovite gneisses, gneissose/granitoids, variable granitic gneisses, biotite and hornblende gneisses, gneisses, granulites, marble, amphibolites, quartzites, mica gneisses, muscovite – biotite ± cordierite ± sillimanite gneisses, granitoids
Precambrian metasediment	Mudstones, shale, phyllites, granitoids, granites, turbidites, mudstones, sandstone, quartzites, grits, shales, slates, muscovite – biotite ± cordierite ± sillimanite gneisses, granitoids, mica schists, meta-sandstones, tuffs, conglomerates, quartzitic sandstones
Plutonic basement	Variable gneissic granitoid rocks

Table 3 Review criteria applied to the historical borehole records compiled from the district water offices

Review tier	Review criteria
1	Borehole record registered in the national groundwater dataset
2	Minimum level of metadata is held including borehole location, lithology, and borehole depth
3	Quality of the pumping test data. Records were removed if there was evidence of significant variation in pumping rate; if the pumping rate was not recorded; or if there was significant difference in transmissivity values calculated from the three analytical methods

Data validation

Review criteria developed to assure the quality of pumping test dataset are outlined in Table 3. Records were removed from the final dataset if: (1) the district borehole record was not identifiable in the Ministry of Water and Environment national groundwater database; (2) there was no locational reference data (village name or coordinates); and (3) the borehole depth, water strike depth and lithology data were not recorded. This produced a dataset of 702 borehole records with pumping test records.

Additional review criteria were applied during the analysis of pumping-test datasets. Two additional analytical approaches were used to analyse pumping-test data in order to cross-check transmissivity values estimated. If computed transmissivity values estimated from the three methods varied by more than one order of magnitude, the borehole record was removed from the final dataset. Borehole records were also removed if there was evidence of significant variation in the pumping rate during the test, or if the pumping rate was not stated. When combined, these review criteria produced the final dataset of 655 pumping test records (Table 1). The relatively large proportion of data found to meet the review criteria, reflects the fact that the initial process to capture records from the district offices was selective, as only borehole records containing

pumping-test data were selected and these tended to be relatively high quality and comprehensive.

Analysis of the pumping test data

Pumping-test records were analysed using BGSPT™ software (Barker 3; Barker and MacDonald 6), which is designed to simulate and analyse pumping test data accounting for well storage based on the generalized well equation of Barker (4). The applied model is suitable for the datasets derived from weathered hydrogeological formations, assuming a semiconfined aquifer of an infinite extent that is overlain by an aquitard and that there is horizontal flow in the unconfined aquifer, vertical flow in the aquitard, and the allowance for well losses. The method is considered to provide reasonable approximations of the transmissivity of fractured aquifers, provided that the borehole penetrates a representative sample of the aquifer, flow is not turbulent and the travel time taken for water to move from the matrix to the borehole is short (Barker and Black 5; Sánchez-Vila et al. 35). Model parameters included transmissivity (T) (constrained by 0.01–100 m²/d), well radius (constrained by 0.03–0.08 m), aquifer losses (constrained by 0.002–0.01 m⁻²/d) and well losses (constrained by 0.002–0.001 m⁻⁵/d², C , and 0.002–0.001 m²/d, B_2). The BGSPT model attempts to minimize R^2 (the sum of squares of residuals – differences between observed and calculated drawdowns).

The brevity of pumping tests and recovery data time series as well as the lack of well observation data, available for each data point in the dataset collated, meant that the Theis Recovery method (Theis 44; Kruseman and de Ridder 1990) and Cooper-Jacob method which can also provide reasonable approximations to evaluate the transmissivity of fractured aquifers, respectively, were less suited to the dataset (Barker and Black 5; Sánchez-Vila et al. 35). These methods were, however, applied to the dataset as part of the quality assurance (QA) procedure and testing of the transmissivity data as discussed in section ‘Data validation’. If

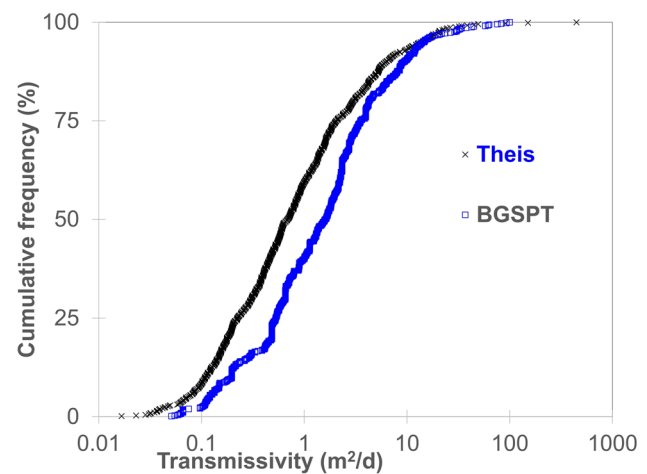


Fig. 3 Comparison of the cumulative percentage distribution of the transmissivity values calculated between the Theis Recovery method and BGSPT

a reliable transmissivity estimate could not be given by the methods, and results between the different methods varied by more than an order of magnitude, then the pumping test record was removed from the final dataset (see section ‘Data validation’).

Results

Transmissivity values

A summary of the borehole depths, yield and static water levels, which support the transmissivity dataset, is given in Table 4. The average borehole depth in the dataset is 69 m; average depth of first water strike is 34 m below ground level (m bgl); and the average static water level is 11 m bgl. The average pumping rate across all of the pumping tests in the dataset is 35 m³/d, and the average duration of the pumping and recovery phases are 197 and 57 min, respectively. Transmissivity values derived by the Theis Recovery

Table 4 Average borehole parameters on which the transmissivity dataset is based

Parameter	1st and 99th percentile	Average	Median	Inter-quartile range
Borehole depth (m), ($n=655$)	19–129	69	69	20
Depth of first water strike (m bgl), ($n=567$)	8–83	34	30	21
Static water level (m bgl), ($n=654$)	1–35	11	9	7
Borehole yield after installation (m ³ /d), ($n=604$)	0.3–15	2	1	2
Average pumping rate during test pumping (m ³ /d), ($n=655$)	6–123	35	25	25
Length of test pumping period (min), ($n=655$)	90–300	197	180	0
Length of recovery period (min), ($n=655$)	0–180	57	60	40
BGSPT Transmissivity (m ² /d) ($n=655$)	0.06–59	4	1.6	3

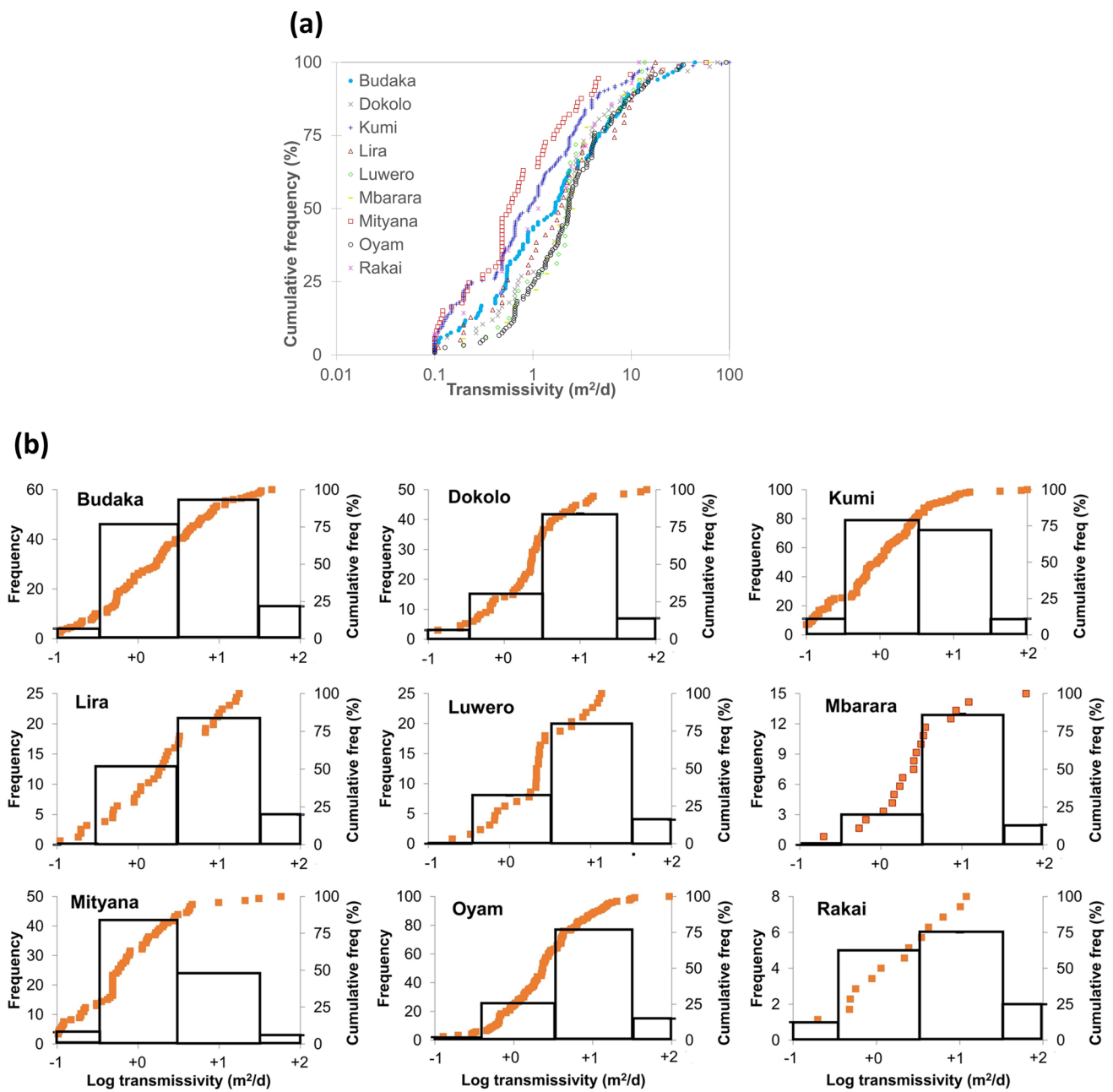


Fig. 4 **a** The final dataset distribution transmissivity values in the dataset, across the nine districts; and **b** the cumulative frequency and histograms of the distribution of the transmissivity data for each district

and BGSPT methods were comparable but with a slightly lower distribution of values estimated by the Theis Recovery method (see Fig. 3). The final dataset and transmissivity used in the analysis of this report are based on the BGSPT method because it accounts for well storage and inefficiency. Further, the short duration of (<2 h) of measuring recovery in the pumping tests means that the Theis method is less appropriate. Low permeability (e.g. $T = 1 \text{ m}^2/\text{d}$) aquifers with boreholes of 6 in. (~15 cm) diameter require at least 2 h of recovery to get 25% accuracy (MacDonald et al. 26).

Final transmissivity values are accordingly based on the BGSPT method.

Transmissivity values estimated from the dataset range from 0.05 to 100 m^2/d with the distribution skewed towards the lower values as indicated by a median T value of 1.6 m^2/d and the interquartile range of the data (Table 4). Only 53% of records have T values of at least 1.4 m^2/d , which Bianchi et al. (7) considered to be the minimum to sustain a standard HPB yield (8.6 m^3/d). The distribution including the cumulative frequencies and histograms of transmissivity values

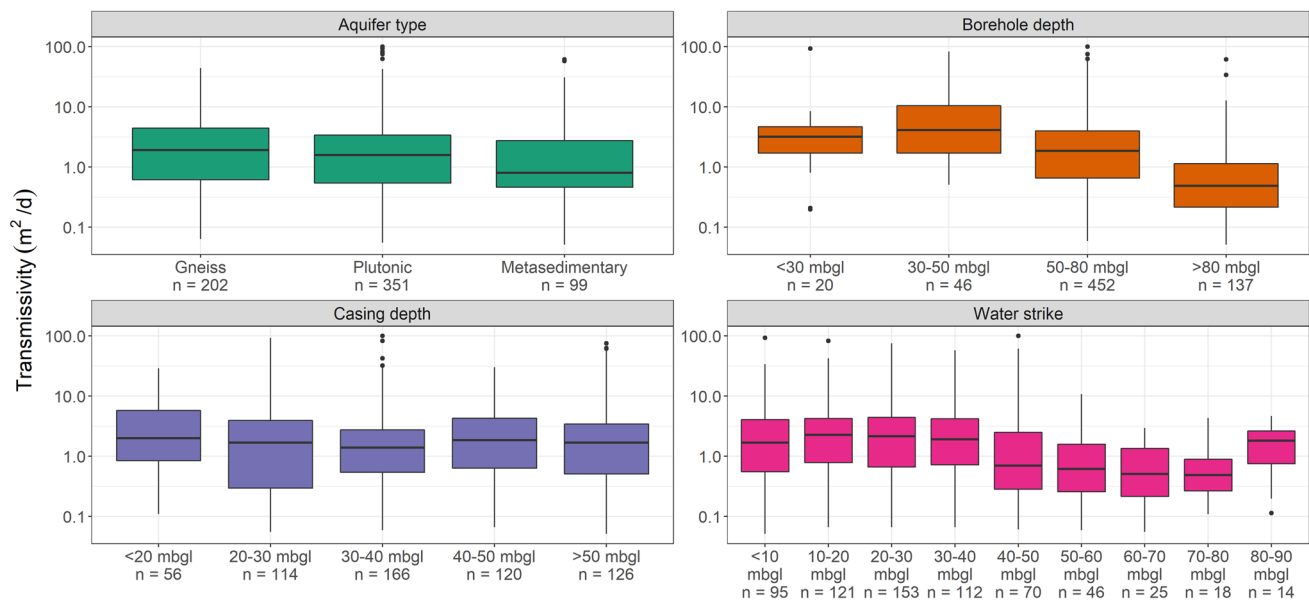


Fig. 5 Transmissivity variations across **a** bedrock aquifer type; **b** borehole depth; **c** casing depth; and **d** water-strike depth

is similar across all the districts within the sample ($n=655$), indicating a pervasive low transmissivity within the weathered and fractured aquifers (Fig. 4).

Variation in transmissivity

To test for systematic patterns in transmissivity, the median and interquartile ranges in transmissivity values were compared against the aquifer rock type, borehole depth, casing depth and water strike (Fig. 5).

Bedrock aquifer type

Transmissivity values are low across each of bedrock aquifer categories with no significant differences among the categories (Fig. 5 and Tables 5, 6, 7 and 8). Median transmissivity values across the bedrock categories are: (1) $1.9 \text{ m}^2/\text{d}$ in the gneissic basement ($n=202$); (2) $0.8 \text{ m}^2/\text{d}$ in the Precambrian metasedimentary ($n=99$); and (3) $1.6 \text{ m}^2/\text{d}$ within the plutonic basement ($n=351$). Exceptionally high transmissivity values occasionally in excess of $30 \text{ m}^2/\text{d}$ exist within the plutonic and metasedimentary rocks but less so in the gneissic basement rocks from several districts. These exceptionally high values are indicated as outliers. No significant statistical difference is found between any of the aquifer categories (Table 5).

Borehole depth

Whilst transmissivity values are pervasively low, some variation is associated with borehole depth (Fig. 5; Table 5). Overall,

slightly higher transmissivity values are associated with borehole depths of $<50 \text{ m}$. Median transmissivity values across borehole depth categories are: (1) $<30 \text{ m}$ depth ($n=20$, $3.2 \text{ m}^2/\text{d}$); (2) $30\text{--}50 \text{ m}$ ($n=42$, $4.1 \text{ m}^2/\text{d}$); (3) $51\text{--}80 \text{ m}$ ($n=453$, $1.9 \text{ m}^2/\text{d}$); (4) $>80 \text{ m}$ depth ($n=140$, $0.5 \text{ m}^2/\text{d}$). Pairwise comparisons indicate statistical significance in transmissivity across the categories, with slightly higher transmissivity values where borehole depths are $<50 \text{ m}$ (Table 5). Given this result, it is important to note that the majority ($>90\%$) of the boreholes within the dataset (and therefore the boreholes recorded to have been drilled within the districts) are greater than 50 m ; with the average depth almost 70 m (Table 4).

Casing depth

For two thirds of the boreholes in the dataset ($n=387$) it was possible to identify the depth of casing where it was installed into fractured bedrock. Casing depths in this subset are thus considered to be a proxy of regolith thickness (e.g. Taylor and Howard 40). Using this subset ($n=387$), a higher median transmissivity of $\sim 3\text{--}4 \text{ m}^2/\text{d}$ is shown to be associated with casing depths $>20 \text{ m bgl}$ ($n=274$), compared to where casing depth is $<20 \text{ m bgl}$ —median T is $\sim 0.8 \text{ m}^2/\text{d}$, $n=113$ (Fig. 5; Table 5).

Depth of initial water strike

Transmissivity values are pervasively low across all categories but a weak relationship between transmissivity and water strike is detected with slightly higher transmissivities associated with initial water strike depths of $10\text{--}30 \text{ m bgl}$

Table 5 Correlation matrices of *p*-value outputs from a Wilcoxon rank sum test for aquifer categories. *Metased* metasedimentary

	Gneiss	Metased	Plutonic
Metased	5.8E-03	NA	NA
Plutonic	0.18	6.9E-02	NA
Volcanic	0.18	0.47	0.22

Table 6 Correlation matrices of *p*-value outputs from a Wilcoxon rank sum test for borehole depth categories

	≤20 m bgl	20–30 m bgl	30–40 m bgl	>50 m bgl
20–30 m bgl	2.1E-01	NA	NA	2.8E-03
30–40 m bgl	1.7E-05	8.5E-03	NA	7.8E-01
40–50 m bgl	1.7E-05	3.3E-03	4.1E-01	4.3E-01
>50 m bgl	1.2E-04	NA	NA	NA

Data in italics denote statistically significant difference in transmissivity values between the categories of aquifer; borehole depth; casing depths; and water-strike depth

Table 7 Correlation matrices of *p*-value outputs from a Wilcoxon rank sum test for casing depths

	≤30 m bgl	30–50 m bgl	>80 m bgl
>80 m bgl	2.9E-05	NA	NA
30–50 m bgl	2.1E-01	NA	9.8E-13
50–80 m bgl	8.3E-02	3.2E-05	9.9E-14
>80 m bgl	2.9E-05	NA	NA

Data in italics denote statistically significant difference in transmissivity values between the categories of aquifer; borehole depth; casing depths; and water-strike depth

(Fig. 5 and Tables 5, 6, 7 and 8). Highest transmissivity values in the dataset—>5 m²/d (*n* = 100)—relate to a median initial water strike depth of 28 m bgl. In comparison, water

strike depths of >30 m bgl correspond with lower transmissivity values (median is 1.0 m²/d) in the dataset.

Tables 5, 6, 7 and 8 show correlation matrices of *p*-value outputs from a Wilcoxon rank sum test. Data in italic highlights where there is some statistically significant differences indicated in transmissivity values between the following categories: (1) aquifer; (2) borehole depth; (3) casing depths; and (4) water-strike depth. It should be noted that because the borehole dataset (*n* = 655) was not randomly sampled or generated against a statistical design, these correlation values are indicative of where differences lie above purely random variations; the values in Tables 5, 6, 7 and 8 should be taken as definitive values of correlation.

Discussion

Factors controlling transmissivity

In Uganda, the geological imprint of long-term deep weathering and erosion helps to explain vertical profiles of regolith and fractured-bedrock (i.e. saprolite-saprock) aquifer systems observed regionally. More localized, lateral (horizontal) heterogeneity is controlled lithologically by the weatherability of the parent bedrock (Taylor and Howard 40). Despite these controls and heterogeneity of the weathered crystalline-rock systems in Uganda, it is notable that median transmissivities estimated for each of the principal bedrock types (i.e. gneissic basement, plutonic basement, Precambrian metasedimentary rocks) are pervasively low across Uganda (<2 m²/d). Within this context, small variations in transmissivity will be significant to the success and sustainability of borehole supplies, even for low-yield HPBs.

Small variations in transmissivity are likely to be explained, in part, by the weatherability of different rock

Table 8 Correlation matrices of *p*-value outputs from a Wilcoxon rank sum test for water-strike depth categories

	0	10	20	30	40	50	60	70	80	110	150
10	0.3	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
20	0.3	1.0	NA	NA	NA	NA	NA	NA	NA	1.0	0.9
30	0.3	1.0	1.0	NA	NA	NA	NA	NA	NA	1.0	0.9
40	1.0	0.1	3.2E-02	3.3E-02	NA	NA	NA	NA	NA	0.9	0.8
50	0.5	8.2E-04	1.4E-04	1.4E-04	0.3	NA	NA	NA	NA	0.8	0.5
60	0.1	8.8E-05	3.1E-05	3.1E-05	2.1E-02	0.3	NA	NA	NA	0.7	0.3
70	0.8	4.9E-02	3.3E-02	3.3E-02	0.8	0.9	0.2	NA	NA	0.9	0.8
80	1.0	0.5	0.3	0.3	0.9	1.0	0.7	1.0	NA	1.0	0.9
90	1.0	1.0	0.9	0.9	1.0	0.8	0.4	1.0	0.9	1.0	1.0
110	1.0	1.0	NA	NA	NA	NA	NA	NA	NA	NA	NA
150	0.5	0.9	NA	NA	NA	NA	NA	NA	NA	1.0	NA

Data in italics denote statistically significant difference in transmissivity values between the categories of aquifer; borehole depth; casing depths; and water-strike depth

types. Gneissic and plutonic basement rocks, which feature higher median transmissivities of 1.6–1.9 m²/d, are typically coarser-grained than metasedimentary rocks comprising phyllites, low-grade schists and quartzites in Uganda; further, they can produce more transmissive regoliths that, below the water table, can include sand-sized fragments of primary minerals such as quartz, orthoclase, and plagioclase from the parent bedrock (Taylor and Howard 39). In contrast, fine-grained minerals such as micas and chlorite in phyllites and low-grade schists weather more readily to clay minerals, constraining their transmissivity and storage of the resultant regolith. Fractured quartzite aquifers can, however, be comparatively high-yielding (e.g. Lugazi in south-central Uganda) but present challenges to drillers in layered metasedimentary systems where these aquifer units can be confined above and below by unstable weathered metasedimentary rocks primarily composed of clay.

The presence, depth and intensity of the weathering profile in weathered crystalline-rock aquifer systems is also likely to drive small ($\leq 1\text{--}5$ m²/d) but significant changes in transmissivity and water supply success. Despite the complexity of these relationships some patterns are shown by the dataset. Highest transmissivities are from boreholes less than 50 m deep, clearly indicating that drilling deeper boreholes does not translate to better supply success or sustainability in Uganda. This supports previous policy approaches in Uganda that if little groundwater is encountered by 50 m bgl, it is more cost-effective to drill a new borehole than to continue to drill to depths of 90–100 m. Higher transmissivity values are also observed where a thicker regolith and weathering profile is indicated to be present by the casing interval (transmissivities of >2 m²/d shown where borehole casing is 30–50 m bgl, and initial water strikes 10–30 m bgl). Too thin a weathering profile is shown to be associated with significantly reduced transmissivity (median values <1 m²/d, where casing depth <20 m). A pattern is also demonstrated between the depth of initial water-level strike and transmissivity; significantly lower transmissivity values (<1 m²/d) are observed where the initial water strikes are deep (>40 m bgl). These associations may indicate a relationship between the degree of weathering and amount of clay present within the weathering profile and transmissivity.

Overall, despite the complexity of the weathered bedrock aquifer systems, the dataset shows the significant influence of the weathered profile to aquifer resource, and patterns can be discerned between transmissivity and the depth and intensity of weathering in the crystalline-rock aquifer systems in Uganda. Developing a better understanding of these relationships will be important to improving the success and sustainability of even low-yielding water supplies in the weathered bedrock aquifer systems in Uganda.

Implications for groundwater development

Overall, the pervasively low transmissivity shown by the dataset (median <2 m²/d) across such a large spatial extent in Uganda stands apart from many other weathered crystalline-rock systems in the tropics. The median transmissivity of weathered bedrock aquifer systems in West Africa and Peninsula India is almost an order magnitude greater than that shown in Uganda (e.g. Razack and Lasm 34; Collins et al. 13). As a result, small variations in transmissivity will be significant to the success and sustainability of borehole supplies in Uganda, even for low-yield HPBs.

Recent analyses by Bianchi et al. (7) to model the productivity of weathered bedrock aquifers in tropical Africa found that key factors controlling the success and sustainability for low-yielding community HPBs were the total thickness (>15 m) and saturated thickness (>5 m) of the largely in situ weathered regolith, and the maximum hydraulic conductivity within the profile. Based on this, Bianchi et al. (7) estimated that a transmissivity of >1.4 m²/d is needed for a HPB to reliably sustain the minimum required yield of 8.6 m³/d for a community supply with intermittent pumping. Less than half of the borehole records within the new transmissivity dataset across a large area of Uganda meet this threshold. Many HPDs in Uganda can be considered to be operating at the margins of their ability to supply the minimum yield required for community supply. Furthermore, these operational pressures will exacerbate any other weaknesses in supply maintenance, construction and siting. These pressures are evident in the observed functionality of community HPB supplies in Uganda. National functionality surveys in Uganda indicate that at any one time approximately 85% of community HPDs are working providing some water (GOU-WESPR 20). Of these, approximately 35% of those assessed to be working are found to provide a sufficient yield (i.e. >10 m³/d), when considering functionality performance, and only 25% did so reliably year-round (Owor et al. 31). These data were generated as part of a detailed functionality survey completed by the UPGro Hidden Crisis project in 2017, and are based on the survey of 200 community HPBs randomly selected across the same nine districts as those within the transmissivity dataset presented by this report (Owor et al. 31; Bonsor et al. 8).

As a result of the low-transmissivity weathered crystalline-rock system, accurate and appropriate borehole siting and design will be pivotal to the long-term functionality performance and sustainability of community HPDs in Uganda. Increased groundwater abstraction through new higher-abstraction pump technologies such as high-intensity solar-powered pumps, should be expected to be challenging in most areas of Uganda. Indeed, higher abstractions demanded by reticulated systems will be difficult, if not impossible, to obtain from single borehole abstractions.

Modelling suggests that sustaining these types of systems requires transmissivity values of $>6 \text{ m}^2/\text{d}$ (Bianchi et al. 7). The compiled pumping-test dataset presented here indicates that these transmissivities are rare in Uganda. Given the constraints of the bedrock aquifer environment in Uganda, a more appropriate approach for increased community water supply may be the development of a larger number of low-yielding HPBs. Revised contractual processes and increased hydrogeological support could support this approach.

In some circumstances, weathered crystalline-rock aquifer systems in Uganda may support increased abstraction—for example, where localised, highly productive sediments overlie the bedrock aquifers providing additional storage and capacity (Taylor et al. 41; Tindimugaya 45). The new dataset, however, shows these circumstances are exceptional, rather than common. The findings from the analysis of this newly compiled transmissivity dataset in Uganda highlight the importance of an informed understanding and characterization of weathered rock aquifer systems, which control the performance, viability and sustainability of community HPBs.

Conclusions

Weathered-bedrock aquifer systems in Uganda are shown to be characterized by pervasively low transmissivities (median $<2 \text{ m}^2/\text{d}$), which stand apart from weathered crystalline-rock systems elsewhere in the tropics. Less than half of the borehole records within the dataset in Uganda exceed the minimum transmissivity ($>1.4 \text{ m}^2/\text{d}$) required to reliably sustain a minimum well yield of $8.6 \text{ m}^3/\text{d}$ for a community HPB with intermittent pumping. In this environment, small variations in transmissivity exert significant influence on the success and sustainability of borehole supplies, even for low-yield HPBs. The dataset provides valuable insight of observed relationships between transmissivity and the depth and intensity of weathering in weathered crystalline-rock aquifer systems in Uganda. Developing a better understanding on the controls to these small variations in transmissivity, alongside accurate and appropriate borehole siting and design will be pivotal to the long-term functionality performance and sustainability of water services in Uganda. The analysis suggests that increased groundwater abstraction through new higher-abstraction pump technologies will be challenging in most areas of Uganda. Given the constraints of the bedrock aquifer environment in Uganda, a more appropriate approach for developing increased community water supply may be the development a larger number of low-yielding HPBs. This study also highlights the importance of compiling and analysing drillers' records and borehole information held

in district water offices. These records often remain unanalyzed but can provide valuable insight and understanding to exploited aquifer systems.

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Data availability The data set of borehole information and transmissivities discussed in this report can be downloaded from the National Geoscience Data Centre of the British Geological Survey (Owor et al. 32). The data set DOI is <https://doi.org/10.5285/e01c3db6-b904-466e-9ab9-0406d909c276>

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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